National Aeronautics and
Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

The Hyperspectral IR Climate Data Record

July 17, 2007

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Overview

- Hyperspectral IR *ESSENTIAL* for climate studies of the atmosphere
- Current and Planned Operational Spectrometer/Sounders measure Hyperspectral IR from 3.3 to 15.4 μm: ***AIRS, TES, IASI, CrIS***
- These Assets are Well Suited to support CLARREO
  - **Past**: Since 2002 from AIRS on Aqua, TES on Aura, to IASI on MetOP and CrIS on NPOESS
  - **In-Perpetuity**: Part of Operational Weather Forecast System
  - **Multiple Orbits**: Additional Points in the Diurnal Cycle
  - **Calibrated**: Accurate and Stable both radiometrically and spectrally
  - **Traceable**: to NIST Standards from Pre-flight to In-Orbit
  - **Validated:** Independently Verified Accurate
  - **Cross-Calibration**: Moderate spatial resolution gives many “clear” observations. Wide swath offers numerous opportunities
  - **In-use**: Spectra and Products Currently Used for Cross-cal and Climate Studies by Scientists
- What are the capabilities of these sensors? Are they good enough to support CLARREO?
- CLARREO can improve upon the current capability but must have adequate spatial, spectral and radiometric resolution and accuracy.

AIRS Science Team

Chahine, M. (TL)	JPL
Aumann, H.	JPL
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Goldberg, M	NOAA/NESDIS
Kalnay, E.	UMD
LeMarshall, J.	JCSDA
McMillin, L.	NOAA/NESDIS
Revercomb, H	U of Wisconsin
Rosenkrantz, P.	MIT
Staelin, D.	MIT
Strow, L.	UMBC
Susskind, J.	GSFC
Brewster, K.	U of Oklahoma
Barker, D.	NCAR
Icano, M.	AER
McMillan, W.	UMBC
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Lord, S.	NOAA/NCEP
Barnet, C.	NOAA/NESDIS
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Tobin, D.	U of Wisconsin
Mlynczak, M	LARC

International Partners

Chedin, A. (Continuing)	CNRS
Rizzi, R. (Continuing)	U of Bologna
Calheiros, R. (Continuing)	Brazil/HSB
McNally, T.	ECMWF
Saunders, R.	UKMO

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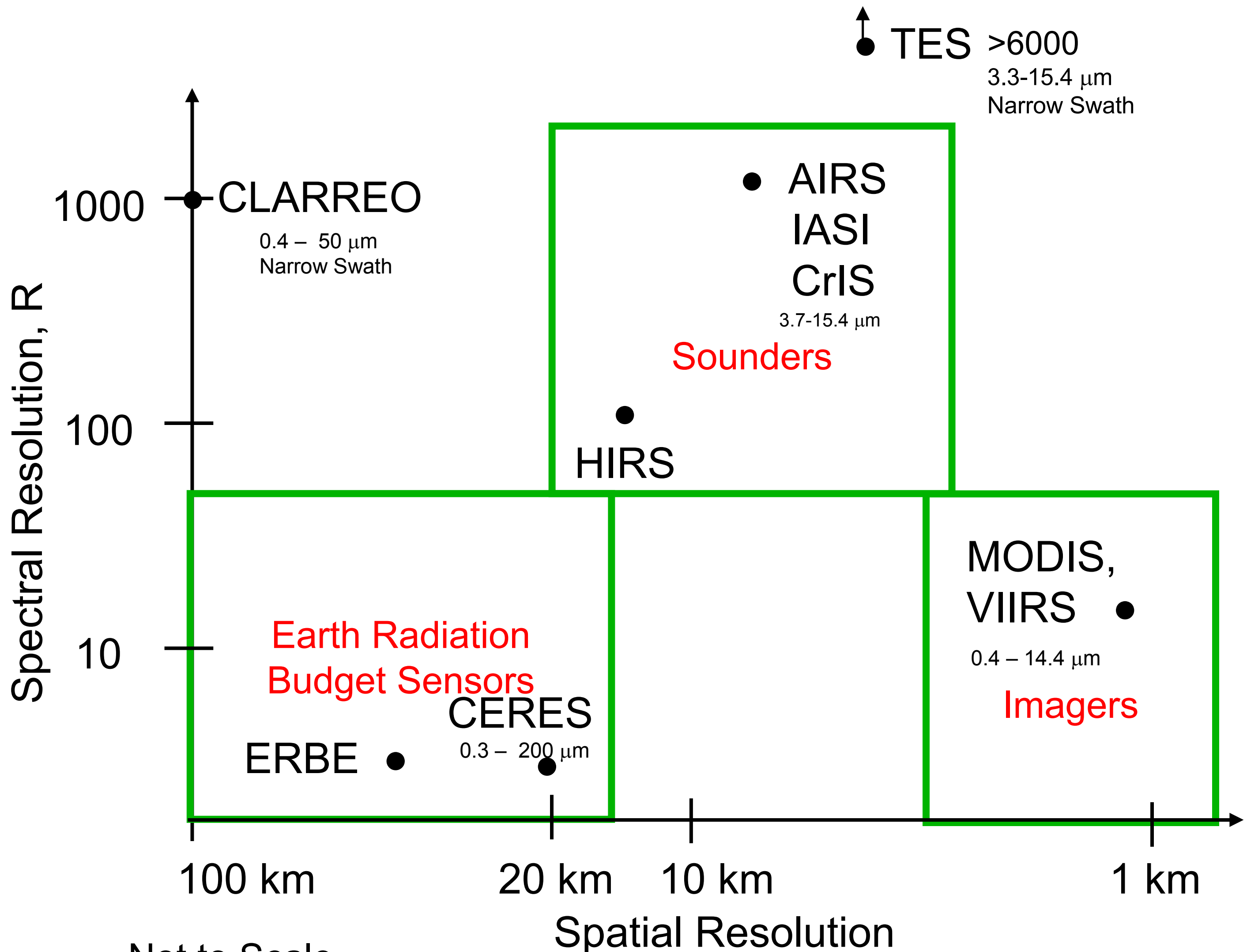
Sounders fall in line with CLARREO Measurement for MW/LW

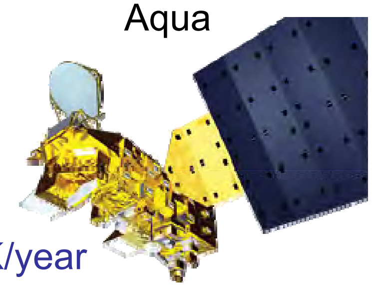


Not to Scale

AIRS, CrIS, IASI have similar requirements

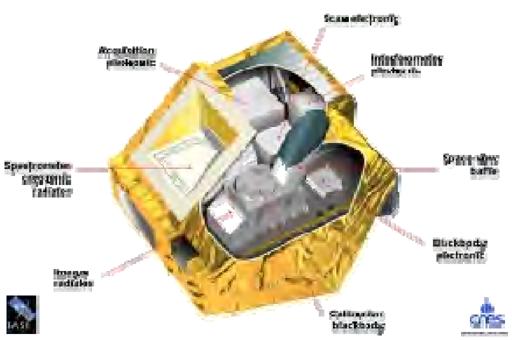
- **AIRS**
  - Spatial: Range ±49.5°, IFOV = 1.1°, 14 km
  - Spectral: 2378 Channels, Stability < 5 ppm
  - 650-1136 cm^{-1}, 0.41-1.05 cm^{-1}
    - 1216-1613 cm^{-1}, 0.95-1.41 cm^{-1}
    - 2181-2665 cm^{-1}, 1.75-2.13 cm^{-1}
  - NEdT: ~0.2K, Accy: < 0.2K, Stability: <8 mK/year
  - 177 kg, 256 W, 0.9 m^3, 1.3 Mbps

Aqua



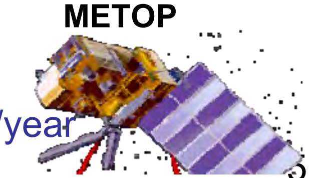
- **CrIS**
  - Spatial: Range ±48.3°, IFOV = 1.1 °, 14 km
  - Spectral: 1302 Channels, Stability < 10 ppm
    - 650-1090 cm^{-1}, 0.625 cm^{-1}
    - 1210-1750 cm^{-1}, 1.25 cm^{-1}
    - 2155-2550 cm^{-1}, 2.5 cm^{-1}
  - NEdT : ~0.2K, Accy : TBD, Stability: TBD mK/year
  - 165 kg, 135 W, 0.5 m^3, 1.5 Mbps

NPOESS

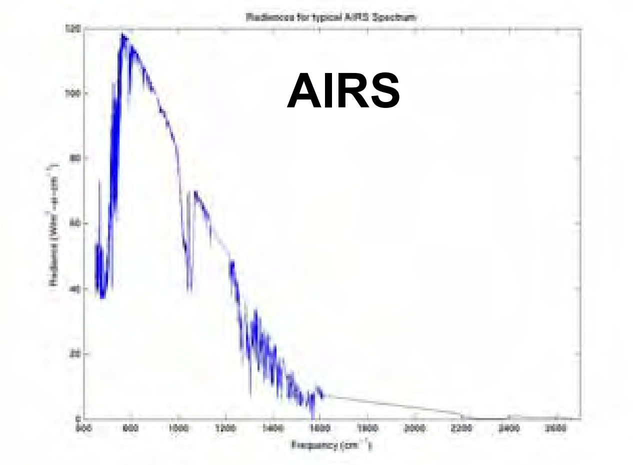


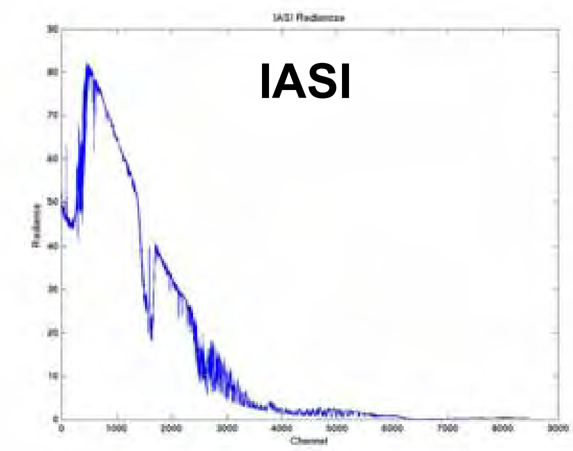
- **IASI**
  - Spatial: Range ±49.0°, IFOV = 0.9°, 12 km, GSD = 18 km
  - Spectral: 8461 Channels
    - 645-1210 cm^{-1}, 0.5 cm^{-1}
    - 1210-2000 cm^{-1}, 0.5 cm^{-1}
    - 2000-2760 cm^{-1}, 0.5 cm^{-1}
  - NEdT : ~0.2K, Accy : TBD, Stability: TBD mK/year
  - 236 kg, 210 W, 1.72 m^3, 1.5 Mbps

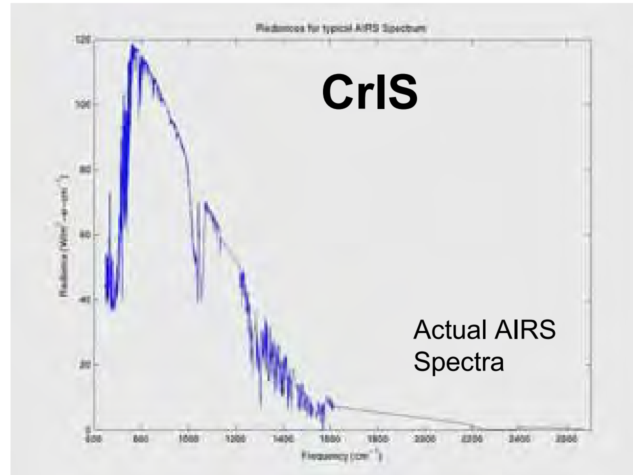
METOP



Sounder Constellation in Place Continuously from 2002 onward





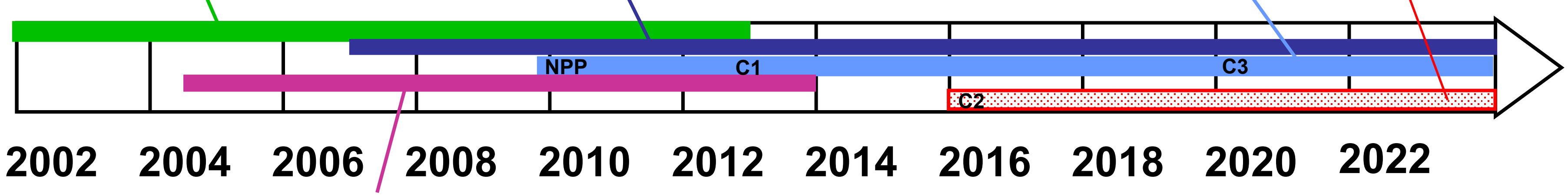


AIRS on Aqua
1:30 PM Orbit
14 km GSD
±49.5° Swath
0.1-0.2K Absolute
10mK/year Stability

IASI on MetOp
10:30 AM Orbit
12 km GSD
±49° Swath

CrIS on NPOESS
1:30 PM Orbit
14 km GSD
±48.3° Swath
C1: 2013
C3: 2020

NPOESS
5:30 AM
C2: 2016
CrIS De-Manifested



TES on Aura
1:30 PM Orbit

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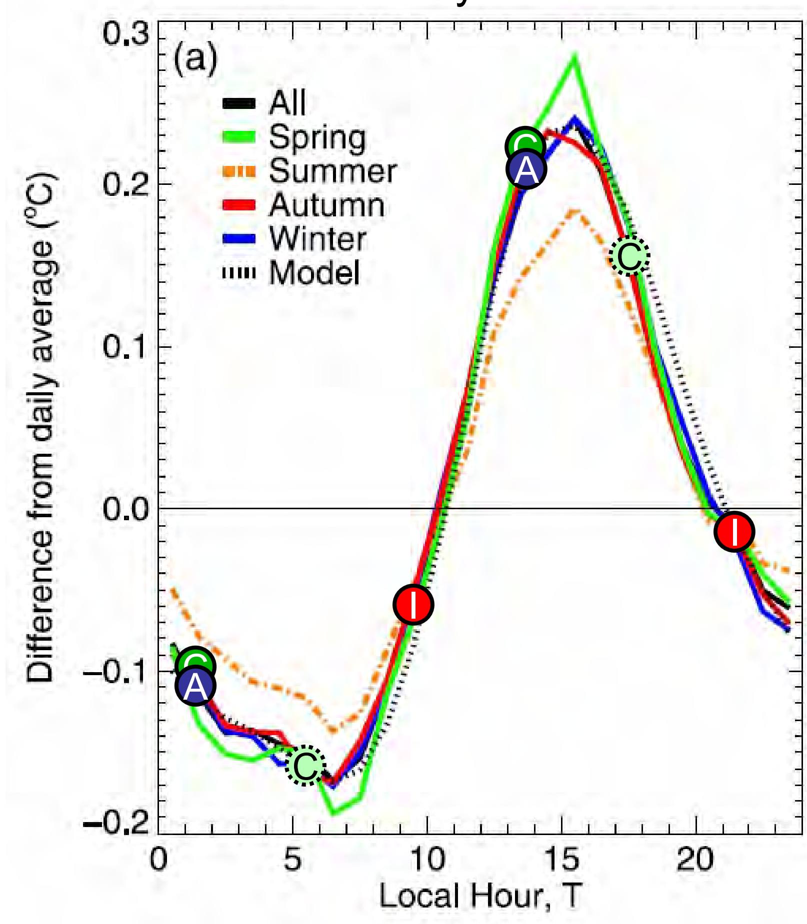
AIRS/CrIS and IASI Provide 4 Points in Diurnal Cycle

- A AIRS: Aqua: 13:30, 1:30
  TES: Aura: 13:30, 1:30
- C CrIS: NPOESS C1 and C3: 13:30, 1:30
- I IASI: MetOp, 9:30, 21:30
- C CrIS: NPOESS C2 (Cancelled): 5:30, 17:30

CrIS on C2 Would Improve Characterization of Diurnal Cycle

Diurnal Cycle of SST



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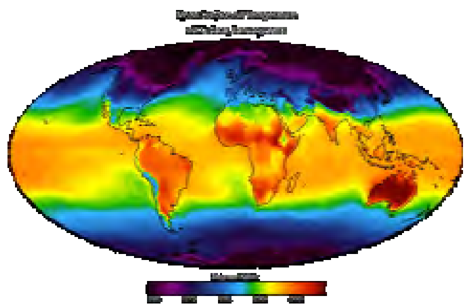
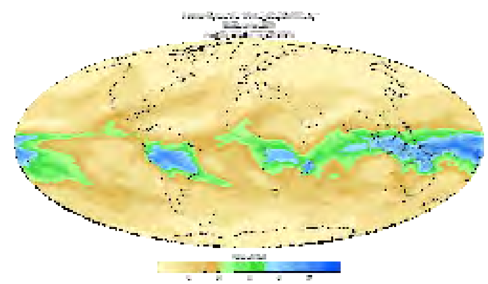
Sounder Data Products Support Climate Processes and Trending

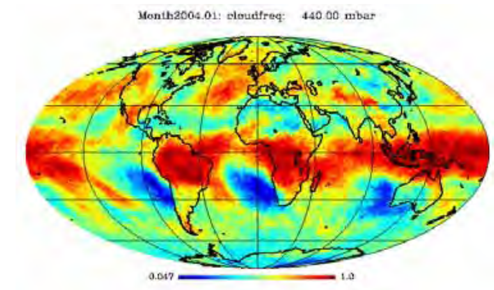
Atmospheric Temperature



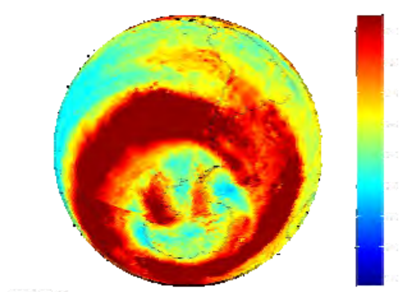
Atmospheric Water Vapor



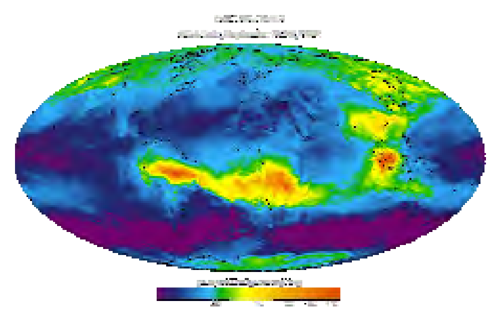
Cloud Properties



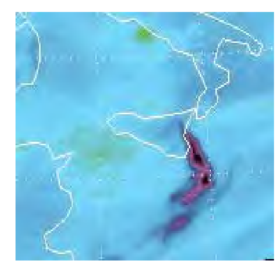
Ozone



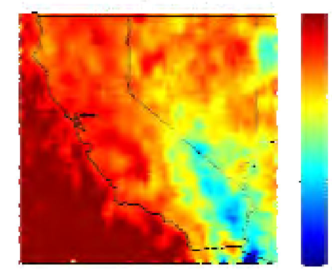
CO



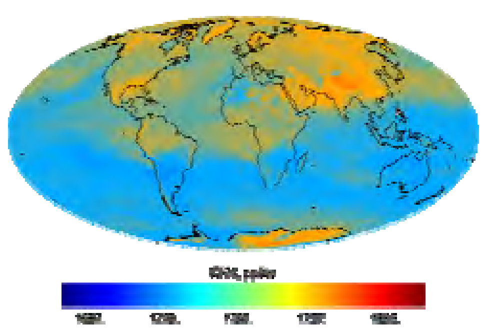
SO2



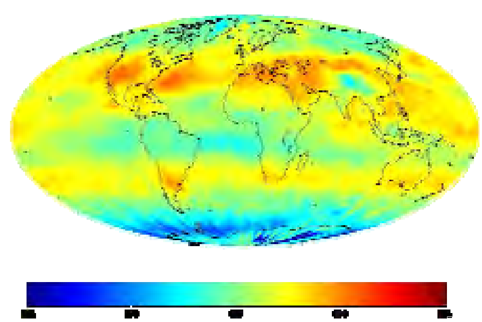
Emissivity



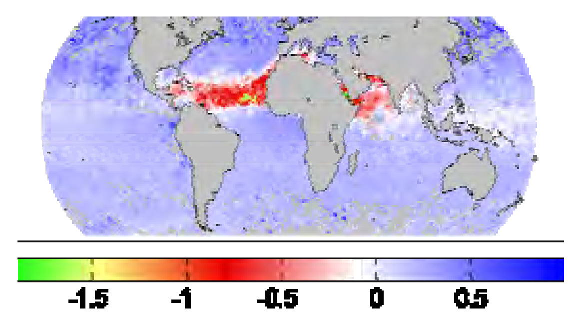
Methane



CO2



Dust



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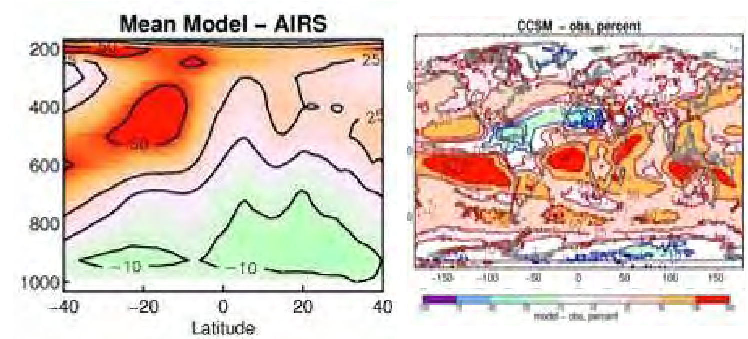
Example: Water Vapor Climate Process Improvement using AIRS Data

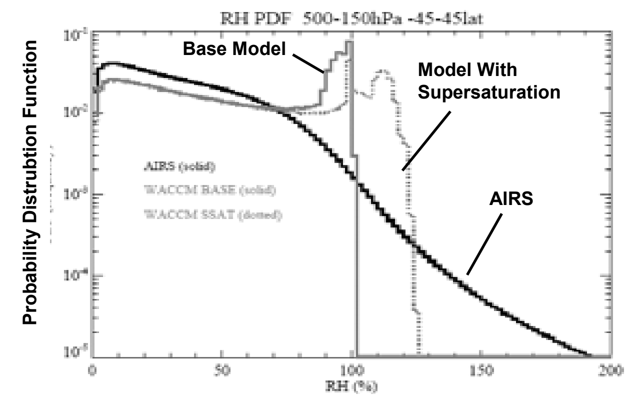
- Coupled Climate Model Validation
  - The models are drier than AIRS observations by 10%-25% in the tropics below 800 hPa.
  - The models are more moist by 25%-100% between 300 and 600 hPa, especially in the extra-tropics.

    **** David W. Pierce, Tim P. Barnett, Eric J. Fetzer, Peter J. Gleckler, Three-dimensional tropospheric water vapor in coupled climate models compared with observations from the AIRS satellite system, GRL, VOL. 33, L21701, doi:10.1029/2006GL027060, 2006***



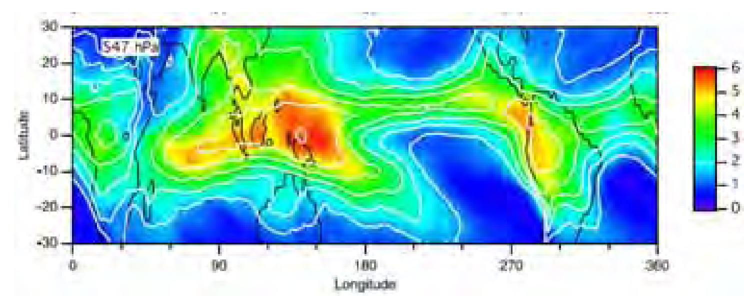
- Water Vapor Parameterization
  - Supersaturation affects amount of water vapor in upper stratosphere which in turns affect amount of clouds
  - Changes Cloud Forcing
    - LWIR: Δ = -7 W/m^2, SWIR: Δ = 8 W/m^2, NET: Δ = -0.6±0.3 W/m^2

    **** A. Gettelman and D. E. Kinnison, The global impact of supersaturation in a coupled chemistry-climate model, Atmos. Chem. Phys., 7, 1629–1643, 2007 www.atmos-chem-phys.net/7/1629/2007/***



- Water Vapor Transport Studies
  - Simple trajectory model with fixed RH limit does a good job of reproducing AIRS annual average water vapor

    **** Dessler, A. E., and K. Minschwaner (2007), An analysis of the regulation of tropical tropospheric water vapor, J. Geophys. Res., 112, D10120, doi:10.1029/2006JD007683, 2007***



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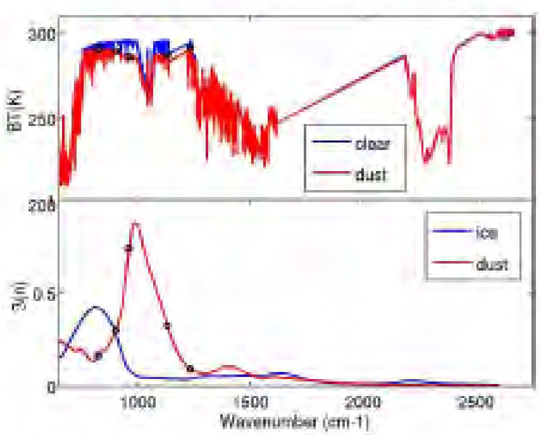
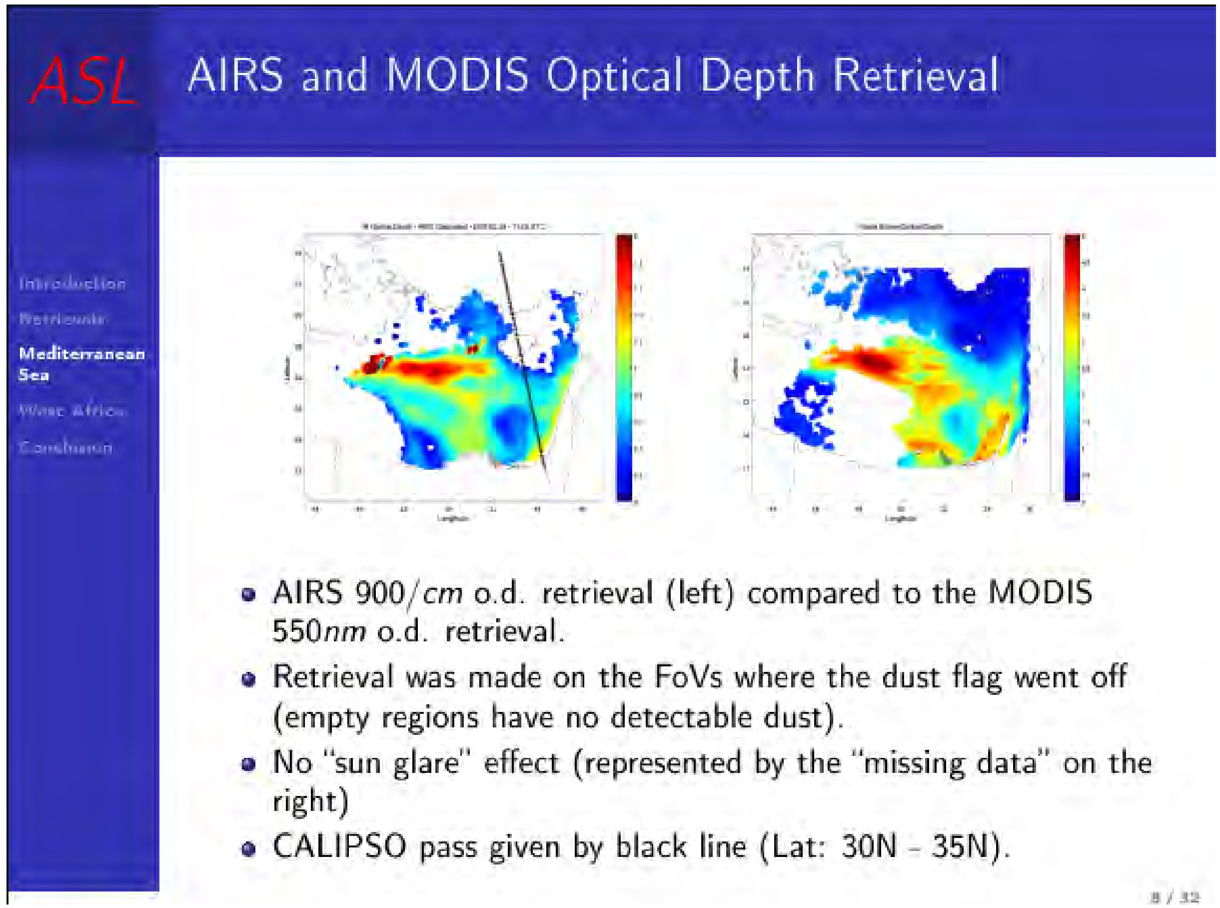
Example: AIRS Measures IR Properties of Dust

Hypsperspectral IR Allows Direct Measurement of Dust LW Radiative Forcing





S. DeSouza-Machado, et. al, GRL, VOL. 33, L03801, doi:10.1029/2005GL024364, 2006

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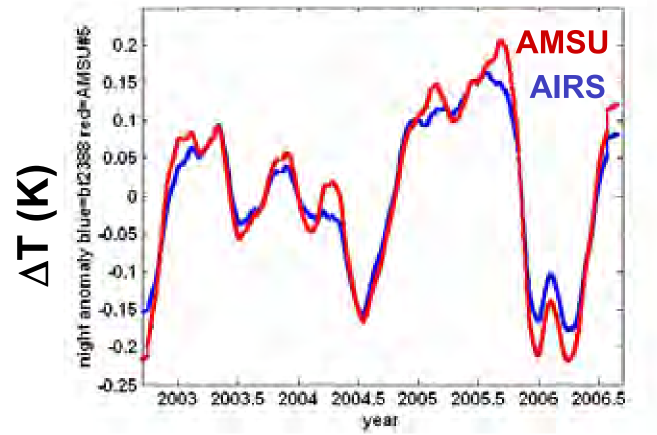
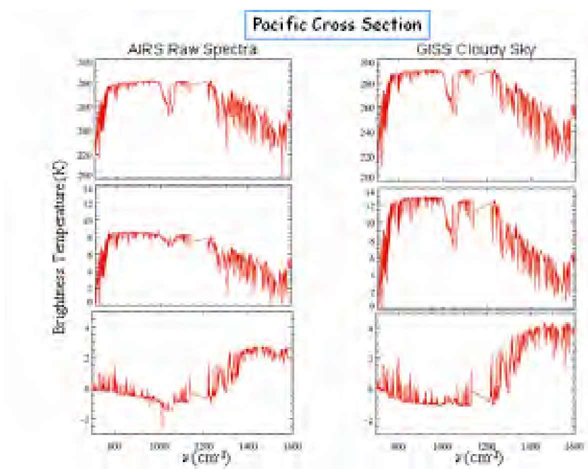
AIRS Spectra Directly Used for Climate Studies

- Trending
  - The four year anomaly of AMSU and AIRS temperatures at 400 mb shows a pronounced quasi-bi-annual fluctuation of about 0.4 K peak-to-peak.
  - This fluctuation severely limits the ability to interpret trends on a four year time scale in terms of climate relevance.
  - It also makes it difficult to compare the mean of four years from today with similar data taken 20 years ago or 20 years from now, even if they were intrinsically accurate at the 100 mK 3 sigma level.
  - Aumann (2007)
- Principal Component Analysis
  - Difference in EOF1 suggest there is a problem in the boundary layer humidity.
  - Huang, X., and Y. L. Yung. (2005). “Spatial and spectral variability of the outgoing thermal IR spectra from AIRS: A case study of July 2003.” J. Geophys. Res.: 110 D12102/2004JD005530.
  - See Yung/Waliser Poster

400 mb Temperature Anomaly





AIRS L1B (Hyperspectral IR) Climate Data Subset Available from GES/DISC

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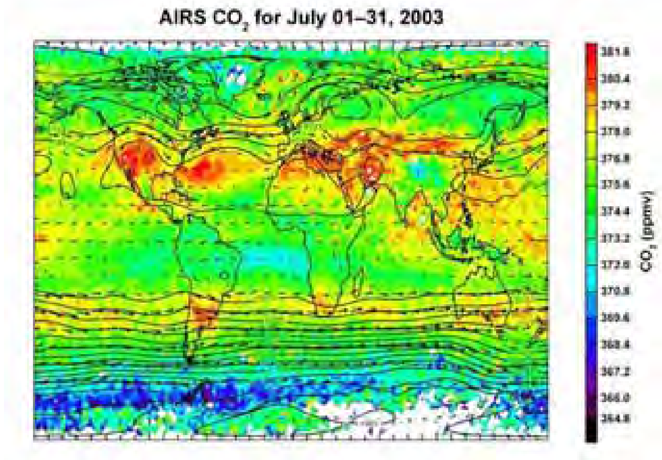
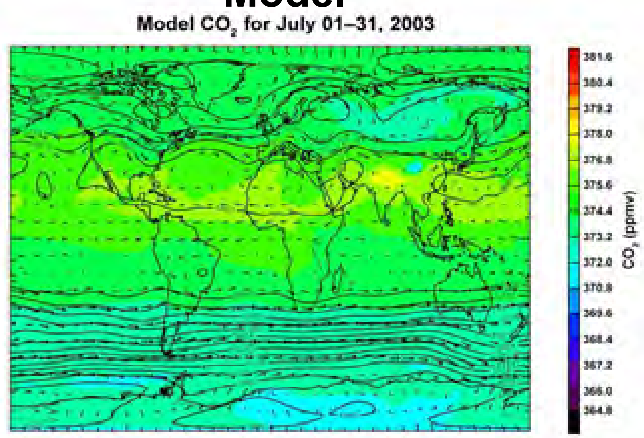
Small CO_2 Signal Trends Only Possible with Sufficient Stability and Coverage

AIRS CO2 Product (Chahine)

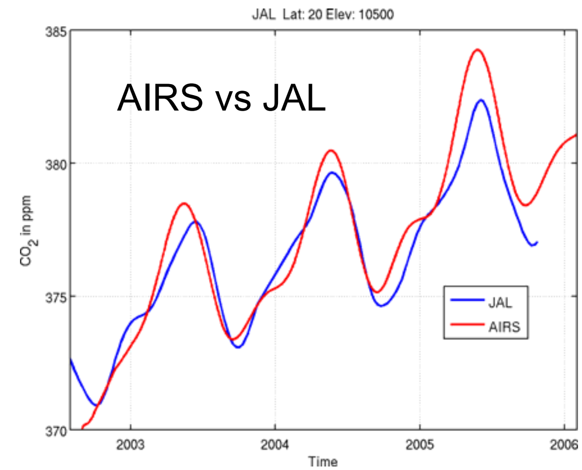
Observed



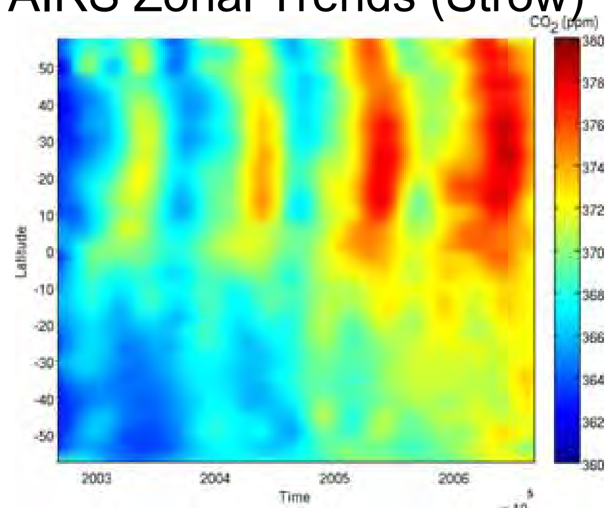
Model



CO2 Trending using Spectra (Strow)



AIRS Zonal Trends (Strow)



Demonstrates <10mK/year Stability

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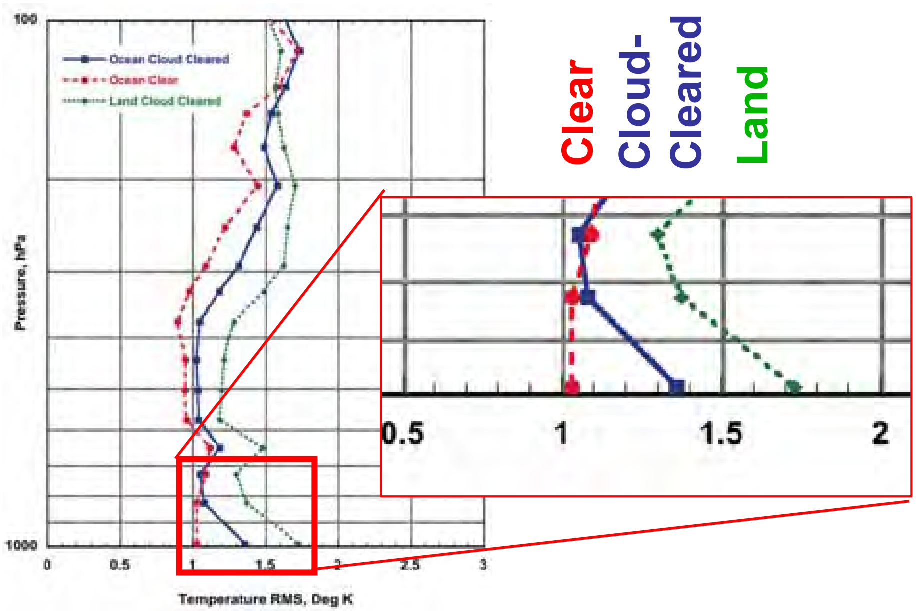
Spatial Resolution Limits Product Accuracy in boundary Layer

Climate Scientists need better products in PBL
Clouds and Emissivity Limit Sounder Accuracy
Higher Spatial Resolution will improve Accuracy

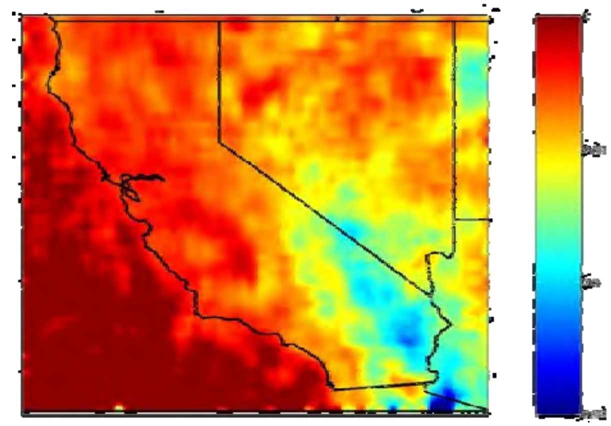
Temperature Profile Error



Emissivity

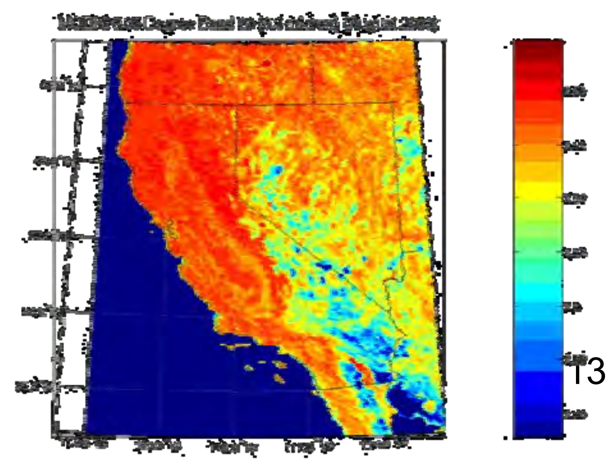
AIRS: 50x50 km

v = 1095 cm^{-1}



MODIS 5x5 km

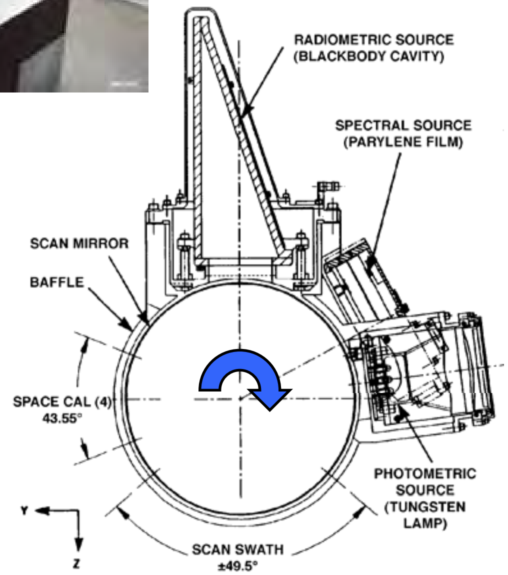
v = 1205 cm^{-1}



AIRS Designed for Stability and Accuracy

AIRS Requirements

- Orbit: 705 km, 1:30pm, Sun Synch
- IFOV : 1.1° x 0.6°
  (13.5 km x 7.4 km)
- Scan Range: ±49.5°
- Full Aperture OBC Blackbody, ε>0.998
- OBC BB EOL Degradation < 15 mK[1]
- Full Aperture Space View
- Solid State Grating Spectrometer
  - IR Spectral Range:
    3.74-4.61 μm, 6.2-8.22 μm,
    8.8-15.4 μm
  - IR Spectral Resolution:
    ≈ 1200 (λ/Δλ)
  - # IR Channels: 2378 IR
- VIS Channels: 4
- Mass: 177Kg,
  Power: 256 Watts,
  Life: 5 years (7 years goal)



[1]K. Overoye, ARS OBC: Emissivity Impact on Brightness Temperature Uncertainty, ADF 762, July 9, 2007

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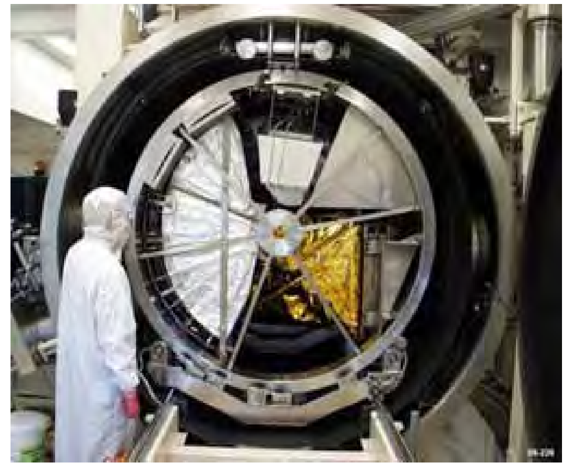
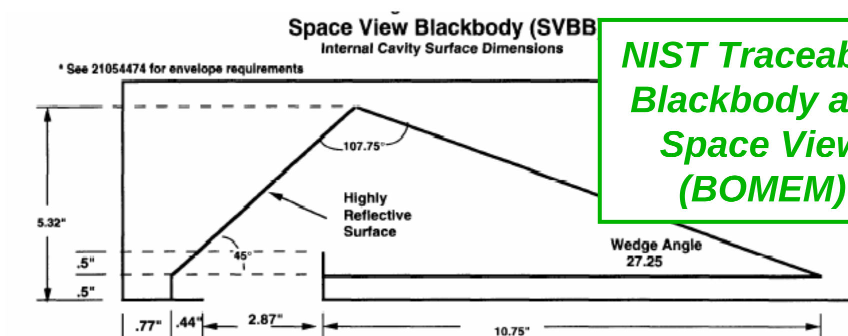
Extensive Pre-flight Calibration on AIRS is Part of Climate Record

- Radiometric Response
  - Emissivity, Nonlinearity
  - Stray Light, Polarization
  - Scan Angle Dependence in TVAC
  - $\varepsilon_{LABB} = 0.9999$, $\delta T = 0.03$K[1,2]
  - Transfer to On-Board Blackbody
  - 2 TVAC Cycles
- Spectral Response
  - SRF Characterization with FTS
  - Channel Spectra Characterized
- Spatial Response
  - Top-hat Functions All Channels
  - Stray Light Excellent
  - Far Field Response Excellent
- Good Documentation
  - Over 400 Design File Memos





Aperture

NIST Traceable[2] Blackbody and Space View (BOMEM)

[1]AIRS Large Area Blackbody Acceptance Report. BOMEM Inc., AI-BOM-039/96, July 2, 1996

[2]8 B. Manum, Thermistor Calibrations, NIST Report 836/259900-98, May 1998

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AIRS Accuracy Estimated Prior to Launch

$$N_{sc,i,j} = \frac{a_o(\theta_j) + a_{1,i}(dn_{i,j} - dn_{sv,i}) + a_2(dn_{i,j} - dn_{sv,i})^2}{1 + p_r p_t \cos 2(\theta_j - \delta)}$$

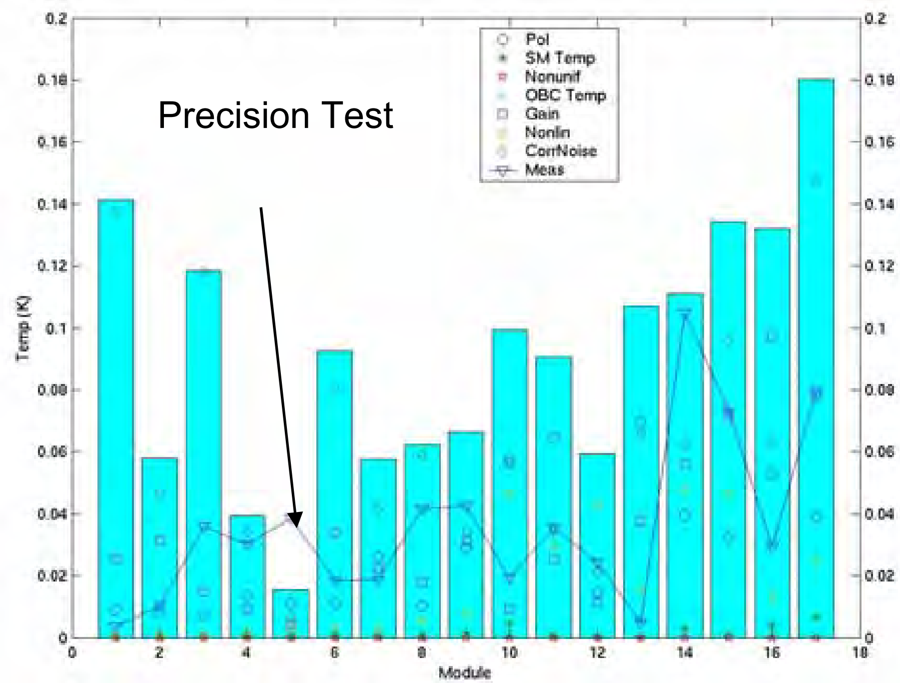
$$a_o(\theta_j) = P_{sm}\, p_r\, p_t[\cos 2(\theta_j - \delta) + \cos 2\delta]$$

$$a_{1,i} = \frac{N_{OBC,i}(1 + p_r p_t \cos 2\delta) - a_o(\theta_{OBC}) - a_2(dn_{obc,i} - dn_{sv,i})^2}{(dn_{obc,i} - dn_{sv,i})}$$

No Change of Cal Coefficients Derived Pre-Launch = Fully Traceable

$N_{sc,i,j}$ = Scene Radiance (mW/m^2-sr-cm^{-1})
Psm = Planck radiation function
$N_{OBC,i}$ = Radiance of the On-Board Calibrator Blackbody
i = Scan Index, j = Footprint Index
θ = Scan Angle. θ = 0 is nadir.
$dn_{i,j}$ = Raw Digital Number in the Earth View
$dn_{sv,i}$ = Space view counts offset.
a_o = Radiometric offset. $a_{1,i}$ = Radiometric gain.
a_2 = Nonlinearity
$p_r p_t$ = Polarization Factor Product
δ = Phase of the polarization

Pre-flight Model
Less than 0.2K (3σ), Absolute Accuracy



T. Pagano et al., "Pre-Launch and In-flight Radiometric Calibration of the Atmospheric Infrared Sounder (AIRS)," IEEE TGRS, Volume 41, No. 2, February 2003, p. 265

T. Pagano, H. Aumann, K. Overoye, "Level 1B Products from the Atmospheric Infrared Sounder (AIRS) on the EOS Aqua Spacecraft", Proc. ITOVS, October 2003

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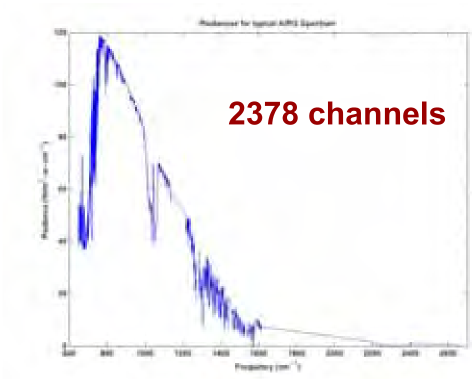
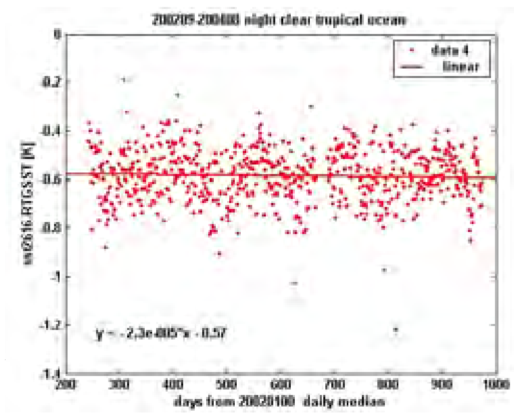
AIRS Radiometric and Spectral Accuracy and Stability Validated In Flight

AIRS Hyperspectral Coverage Climate Data Record (CDR) over 5 Billion Spectra

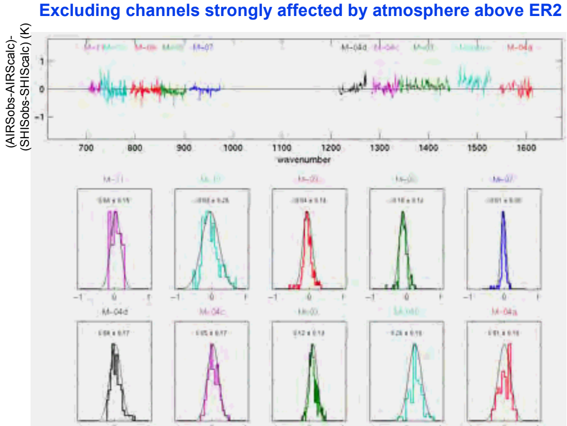


AIRS Radiometric Performance: Stable to <8mK/Y – H. Aumann (JPL)



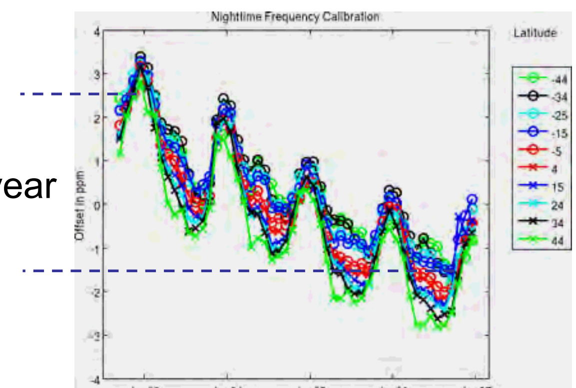
Scanning HIS Validates Rad Accy to 0.2K – H. Revercomb (UW)

Final "Comparison 2" (21 November 2002)
Excluding channels strongly affected by atmosphere above ER2



AIRS Frequencies Stable Knowledge to < 1 PPM - L. Strow (UMBC)

< 1 ppm/year



Reference: JGR, VOL. 111, April 2006

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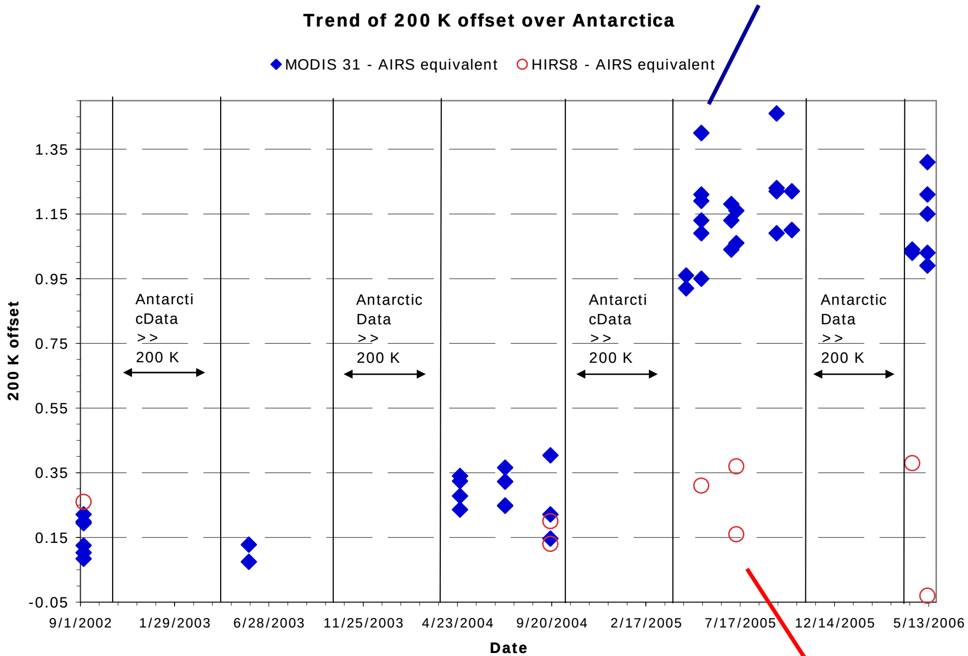
Cross-Calibration and Comparison Successful with Sounders

AIRS-MODIS/HIRS Trend in Radiometric Calibration Dome Concordia

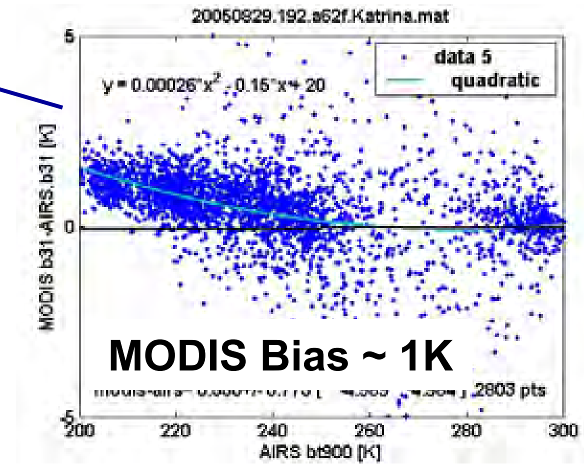


Shift in MODIS Calibration Algorithm V4 to V5

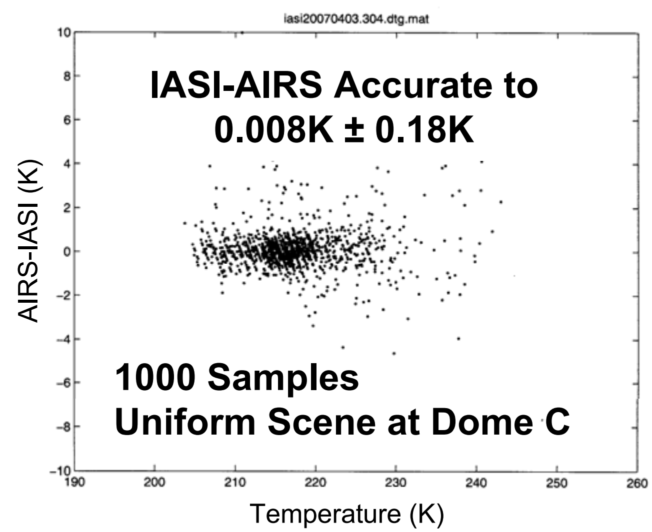
HIRS Stable

S. Broberg, Evaluation of AIRS, MODIS, and HIRS 11 micron brightness temperature difference changes from 2002 through 2006, SPIE 6296-22, August 2006

Cross- Calibration



Cross- Comparison



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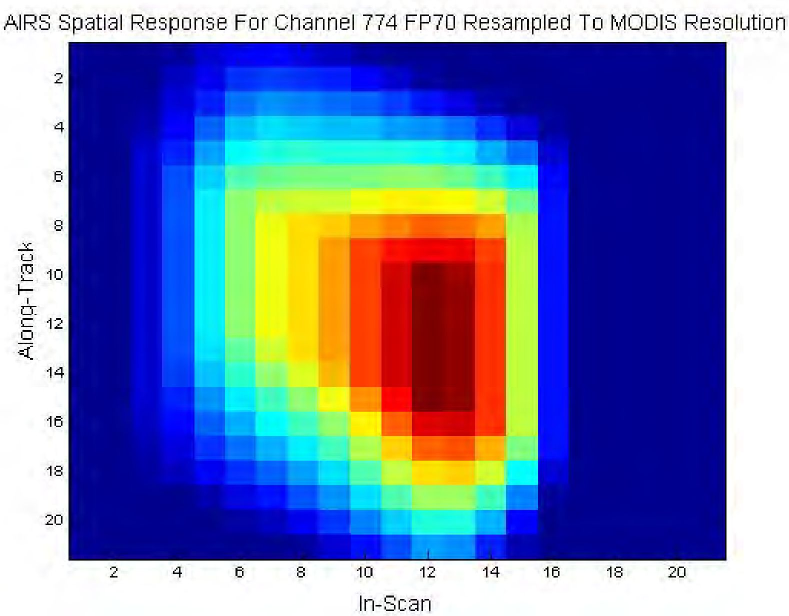
Knowledge of Spatial Response Helps but Not Good Enough for Cross-Calibration

Spatial Response Function
Must be well known
Channel 774, FP 70

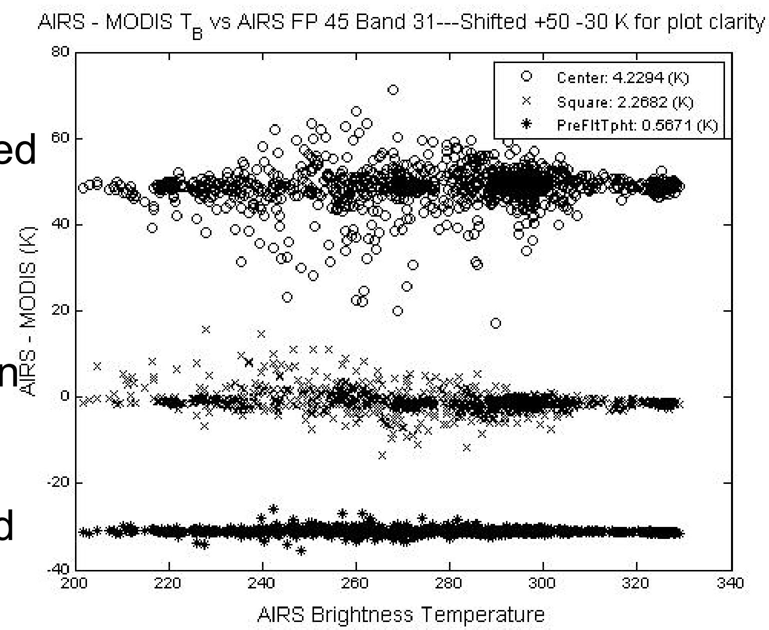


AIRS-MODIS
Non-uniform Scene

Uncorrected
4.2K

Simple
Correction
2.26K

Corrected
0.57K



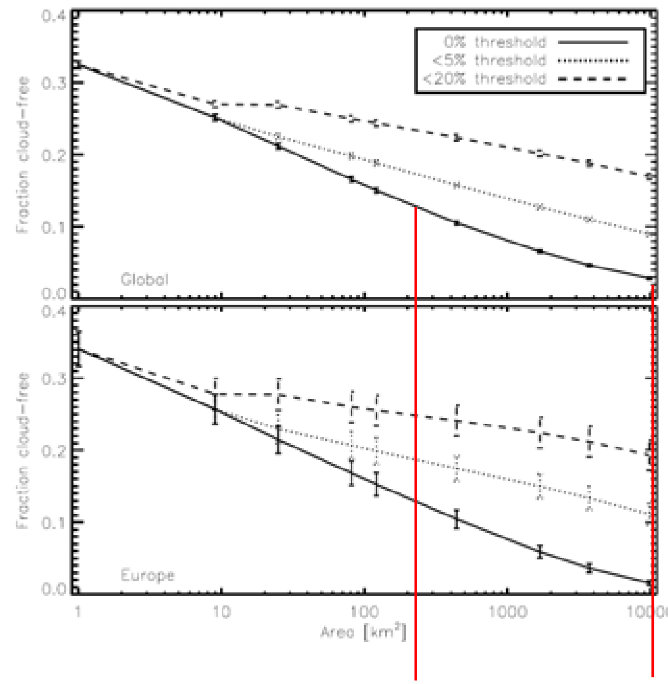
"Noise" in non-uniform scene leads to need for clear-uniform

D. Eliott, et. al, "The Impact Of the AIRS Spatial Response On Channel-To-Channel and Multi-Instrument Data Analyses", Proc. SPIE, 6296-01 (2006)

Validation Requires Good Spatial Resolution and Coverage

- Validation Essential
  - All instruments must be validated using in-situ observations
  - Radiometric: Buoys, Aircraft, ARM Sites
  - Spectral: Atmospheric Lines
- Validation Requirements
  - ~1000 Samples Per Comparison
  - Moderate Spatial Resolution (<15 km)
    - Allows direct comparison with aircraft
    - Allows sufficient number of clear samples
    - Improves Science Resolution
  - Wide Swath (> 45°)
    - Allows more opportunity for cross-comparison and simultaneous in-situ observations
  - Good NEdT (< 0.2K)
    - For least number of samples per comparison

Fraction Clear vs Area[1]
For 1K Cloud Contamination



15 km, 15%
100 km, 2%

[1]J. Krijger et. al, The effect of sensor resolution on the number of cloud-free observations from space, Atmos. Chem. Phys. Discuss., 6, 4465-4499, 2006, www.atmos-chem-phys-discuss.net/6/4465/2006

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Summary and Recommendations

- Multiple Hyperspectral IR Assets Available: AIRS, IASI, CrIS and TES
  - Accurate and Traceable to NIST Standards
  - Stable for long-term observations
  - Offers multiple orbits: 10:30 am, 1:30 pm.
  - Allows starting climate record in 2002 and continues indefinitely
  - NPOESS should re-manifest CrIS on C2 spacecraft for improved diurnal coverage by offering 5:30 am orbit
- Sounders currently in use for Climate Questions in IR
- Higher Spatial Resolution Needed to Improve Boundary Layer Products
- Cross-calibration requires clear-uniform scenes
  - Very few clear-uniform scenes at 100 km
  - Higher spatial resolution required to cross-calibrate and validate
- Can CLARREO cross-calibrate Sounder Constellation? Yes if…
- Recommendations for CLARREO to improve Constellation Accuracy
  - Good Spatial Resolution (<15 km), Wide Swath (> 45°)
  - High Spectral Accuracy (< 1 PPM) and Stability (< 1 PPM/Year)
  - Good NEdT (< 0.2K), Accuracy (<0.1K)
  - Future generations expect CLARREO to be at least as good as Sounders
  - Technology in place to achieve these requirements cost effectively
- Sounder science community ready to support the CLARREO concept